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Fletcher, B.

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Space and Naval Warfare Systems Center
53560 Hull Street
San Diego, CA 92152-5001

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14. ABSTRACT

Robotic vehicle systems, both remotely operated and autonomous, are playing increasing roles in underwater mine countermeasures (MCM) around the world. The current capabilities of MCM vehicles are largely dictated by the capabilities and limitations of present-day remotely operated vehicles (ROVs). While ROV capabilities drive present MCM functions, the emerging capabilities are driven by the development of Autonomous Underwater Vehicles (AUVs). A few prototype systems exist, with more under development. Future directions of MCM development will largely be determined by operational requirements rather than technical issues. The technologies exist or are under development to solve many of the current challenges, including wide-area coverage, operation in the surf zone, automated identification, and effective neutralization. Representative systems and technologies will be discussed in light of these current and future capabilities.
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U	U	U	UU	9	(619) 553-3859

Worldwide Undersea MCM Vehicle Technologies

Barbara Fletcher

Space and Naval Warfare Systems Center San Diego

ABSTRACT

Robotic vehicle systems, both remotely operated and autonomous, are playing increasing roles in underwater mine countermeasures (MCM) around the world. The current capabilities of MCM vehicles are largely dictated by the capabilities and limitations of present-day remotely operated vehicles (ROVs). All but one of the in-service systems today are ROVs, albeit many have self-contained power supplies and many automated functions. Current operational capabilities of these vehicles are largely concentrated in the identification and neutralization roles. While ROV capabilities drive present MCM functions, the emerging capabilities are driven by the development of Autonomous Underwater Vehicles (AUVs). With the elimination of the tether, much wider areas can be covered in a more efficient and covert manner. A few prototype systems exist, with more under development. Future directions of MCM development will largely be determined by operational requirements rather than technical issues. The technologies exist or are under development to solve many of the current challenges, including wide-area coverage, operation in the surf zone, automated identification, and effective neutralization. Representative systems and technologies will be discussed in light of these current and future capabilities.

OVERVIEW

There are four main steps to the underwater mine countermeasure task: detection, classification, identification, and neutralization. Detection denotes the presence of an object of interest, generally found with a long-range, ahead-looking sonar. At the classification level, a detected object is determined to be "mine-like" or non-"mine-like". This determination may be based on a number of factors including relative target size and the geometric characteristics of the sonar shadow. Classification is generally based on sidescan or high frequency sonar images. At the identification level, mine-like contacts are determined to be mines or non-mines. Visual imagery is generally required in order to make an absolute identification. Neutralization refers to disposal of the mine so that it no longer represents a threat. In some instances, basic classification is sufficient for route planning and avoidance.

Underwater vehicle systems can perform a wide variety of tasks related to these missions, generally with specific systems designed for the individual task areas. Currently, ship or helicopter-based systems are most commonly used for detection and classification, while remotely operated vehicles are used for identification and neutralization. Autonomous vehicles are now emerging as an effective means of performing detection and classification with increased standoff distance and covertness.

REMOTELY OPERATED VEHICLES (ROVs)

In the area of MCM, remotely operated vehicles (ROVs) are the most commonly used form of vehicles. These teleoperated systems are controlled via a hard wire or fiber optic link. While many of these vehicles have some automated functions (auto-depth, auto-heading, etc.), they do require having a human operator in the loop at least in a supervisory capability. The presence of the tether provides for real-time data transmission and control through a high-bandwidth connection. There are no real limitations on power, as it is generally supplied from the surface. The tether, however, is also the primary disadvantage of the ROV, providing a hard limit on the range that can be covered and imposing severe performance limitations both hydrodynamically and operationally. Nonetheless, ROVs are a mature technology, providing the standard mechanical platforms for mine identification and neutralization. There are a number of systems in operation world-wide, some of which are described below and summarized in Table 1.

Table 1: Principal Mine Countermeasure Remotely Operated Vehicles

Name	Manufacturer	Number Built (Est.)*	Size (m) l x w x h	Weight (kg)	Depth (m)	Speed (kt)
Sea Eagle Double Eagle Double Eagle Mk 2	Bofors Underwater Systems AB Sweden	15 ? 7+	1.3 x 0.76 x 0.4 1.9 x 1.3 x 0.8 2.1 X 1.3 X 0.5	? 400 340	500 500 350 / 500	3 5 6
Dolphin / Dorado	International Submarine Engineering Canada	10	7.5 x 1.0 dia	3275	3	5 / 16.5
MIN Mk 2	Consorzio SMIN Italy	12		1150	300	6
MNV AN/SLQ-48	Raytheon USA	57	3.7 x 0.9 x 1.2	1247	>200	6
Minesniper	Kongsberg Simrad Norge A/S Norway	8	1.35 x 0.45 x 0.2	26.5	500	6
MMUROV	Benthos USA	2	1.82 x 0.9 x 0.76	173	300	4
Pap 104 / Mk5	Societe ECA France	319 (104) + 57 (Mk5)	3 x 1.3 x 1.3	330	300	6
Phantom HD2 Phantom HVS4 Phantom S2	Deep Ocean Engineering USA	35 12-15 10 (military)	1.4 x 0.65 x 0.59 1.6 x 0.84 x 0.59 1.5 x 0.85 x 0.66	58 82 118	300 300 300	3 4 3+

Table 1: Principal Mine Countermeasure Remotely Operated Vehicles (continued)

Name	Manufacturer	Number Built (Est.)*	Size (m) l x w x h	Weight (kg)	Depth (m)	Speed (kt)
Pinguin B3	STN ATLAS Elektronik GMbH Germany	40+	3.5 x 1.5 x 1.2	1350	200	6 / 8
Pluto Pluto Plus Pluto Gigas	Gayrobot Switzerland	70 25 1-2	1.68 x 0.6 x 0.65 2.1 x 0.6 x 0.61 3.32 x 0.61 x 0.78	130 315 600	300 350 350 / 600 / 1000	4-5 6 7-8
Seafox / Seewolf	STN ATLAS Elektronik GMbH Germany	unknown	1.4 x 0.4 x 0.2	Unk	Unk.	6
Super SeaROVER	Benthos USA	20 (military_	1.4 x 0.7 x 0.63	80	300	5
Trail Blazer	International Submarine Engineering Canada	2	2.63 x 0.64 x 0.86	772	500	5.75

*Built for primary MCM use

Dedicated MCM ROV Systems

There are many ROV systems available world wide, ranging in size from hand-held to tractor trailer sized. The majority of ROVs built specifically for MCM are in the mid-range, many of which are described below.

Sweden's contribution to MCM vehicles has been the Eagle series of vehicles, developed by Bofors Underwater Systems AB, SUTEC. The first system, the Sea Eagle is a militarized version of the commercial Sea Owl MkII. Fifteen were delivered to the Royal Swedish Navy, starting in 1984. Two notable features of these systems are the manipulator arm and control system. The extensible manipulator arm is used to place a charge next to a mine while maintaining a safe standoff distance. An interesting control aspect of the Eagle series is its ability to operate in any orientation, including upside down. The later versions of the vehicle, Double Eagle and Double Eagle Mk II, are significantly larger, with corresponding increases in depth and speed. Eight Mk I and 24 Mk II units have been built and are operated by the Swedish and Royal Danish Navies.

The Italian MIN (Mine Identification and Neutralization) system was developed and produced by Alenia Elsag Sistemi Navali and Riva Calzoni. It has the capability to identify and neutralize both bottom and moored mines. The system is somewhat unique in it's construction, as it is powered by a closed-circuit oleopneumatic accumulator to minimize the noise and magnetic profile. Four MIN MK1's are operational aboard Italian Navy minehunters and 8 MIN Mk2's are being delivered for the Italian Gaeta class minehunters.

One of the most capable MCM ROVs is the US Navy's AN/SLQ-48(V) Mine Neutralization System (MNS) (Figure 1), manufactured by Raytheon. Using a conventional electro-mechanical cable, the vehicle can reach a speed of 6 kt, while carrying two cable cutters and a bomblet. An alternative mission package combines the bomblet with a cable grabbing capability for the destruction of moored mines. It has a high resolution sonar, low light TV and meets stringent military specifications. Particular attention has been paid to the reduction of the acoustic signature due to the hydraulic components on the vehicle. It is operated by the US Navy, with 57 vehicles built that operate from the fleet of 14 full ocean MCM (Mine Counter Measure) ships and 12 coastal MHC (Mine Hunter Coastal) ships.

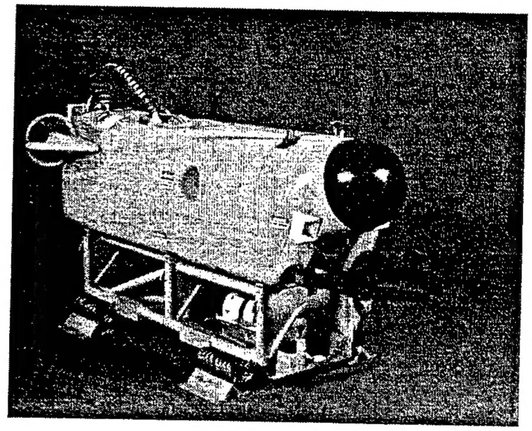

Figure 1: Mine Neutralization Vehicle AN/SLQ-48

The workhorse, and one of the oldest ROVs used in MCM, is the PAP system developed by ECA of France. The vehicle has evolved from the PAP 104 with its bottom hugging drag weight to the fully capable PAP Mark 5 with its 6 kt speed, 300 m depth, and 130-kg explosive charge payload capability. It is operated through an expendable fiber optic cable using an onboard supply of sealed lead acid batteries. The PAP line of vehicles has sold more than any other MCM vehicle, exceeding 370 sold to over 15 navies worldwide.

The German Navy uses the battery operated Pinguin B3, developed by STN Systemtechnik Nord. With the input of target information, the vehicle can run almost automatically towards a mine-like object. Video and sonar data is transmitted over a 1000 m, reusable fiber optic link to the control station. Once a mine has been positively identified, the Pinguin can drop a mine disposal charge for its destruction. A second charge allows an additional target to be prosecuted before the vehicle must be recovered. The vehicle can also carry a special anti-moored mine device which will destroy a moored mine. Over 30 of these vehicles have been built and are in service with the German Navy's 'Frankenthal' class minehunters.

Switzerland has provided the Pluto series of vehicles, developed by Gayrobot-Undersea Technology. The Pluto systems are battery powered, using a 2000 m reusable fiber optic cable for data transmission and communication. The vehicles have low magnetic and acoustic signatures and are resistant to shock and vibration to MIL-spec standards for minehunting.

The latest version is the Pluto Gigas, with double the power of the Pluto Plus, increased endurance, greater depth, and a payload of 2 charges. The original Pluto system has 70 units in service with 10 navies; the Pluto Plus has 25 units in service; and the Pluto Gigas is currently being demonstrated to potential customers.

Canada's contribution, by International Submarine Engineering Ltd., is the Trail Blazer 25 with a 5.5 kt speed, 500 m operating depth and 100 kg payload. Two have been built and are operated by Fairey Systems.

General Purpose ROVs

In addition to the dedicated MCM systems there are a wide variety of general purpose ROV systems commercially available. Many of these, particularly those in the small to mid-range sizes, can be easily adapted to the MCM tasks of identification and neutralization. Several of these have been widely used including the Phantom and SeaROVER series of vehicles.

The Phantom series of vehicles, built by Deep Ocean Engineering, USA, have been widely used for inspection and light manipulative tasks in both commercial and military applications. Eleven navies have purchased Phantoms for general military use including use as MCM platforms. The HVS4 model (Figure 2) was developed specifically for MCM applications. With their small size and reasonable payload capacity, these versatile vehicles are certainly potentially useful in the MCM roles of mine identification and neutralization.

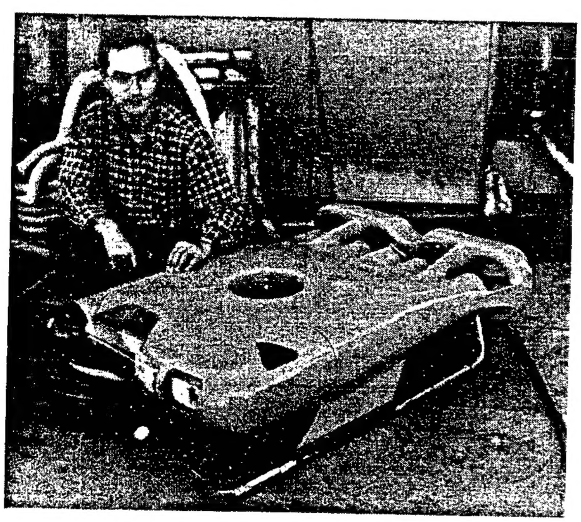

Figure 2: The Phantom HVS4

The Benthos (USA) Sea ROVER vehicles are general purpose inspection systems which have been adapted and evaluated for use as MCM systems. A wide range of sensors and payloads may be outfitted, including inspection and neutralization devices. Twenty of these vehicles were sold to NAVSEA in 1989 and used in the Persian Gulf for MCM operations.

Expendable Systems

A new class of vehicles is emerging, designed as a compact, one-shot mine disposal system. Low-cost and self-propelled, the vehicle is deployed from a surface vessel and guided to the previously detected target via an expendable fiber optic link. Once the target is located using a short-range sonar and video, a shaped charge is used to neutralize the mine. Several systems have been designed and built along these lines, primarily by European concerns. The Archerfish is built by GEC-Marconi Underwater Weapons Division in the United Kingdom, and it was designed to meet the requirements for the updated UK Hunt class vessels. Another is the Minesniper built by Kongsberg Simrad Norge A/S, Norway. The Seafox, developed by STN ATLAS Elektronik GmbH, Germany, is yet another with a Seewolf variation that will carry a larger blast charge for the destruction of buried mines. Full scale development of the Seafox began in 1993, with incorporation on the German 'Hameln' class minesweepers scheduled for 1997. In the US, the Seafox is being adapted for airborne deployment and marketed by Lockheed Martin as the Airborne Mine Neutralization System (AMNS).

AUTONOMOUS UNDERWATER VEHICLES (AUVs)

Autonomous underwater vehicles (AUVs) are emerging as a major platform for the mine detection and classification tasks. While designed to operate independently of continual human control, many of these do have some communication link used for the transmission of data, but not for direct commands and control. With no hard tether, an AUV can cover far greater ranges than an ROV, providing a far greater standoff capability for manned platforms. The disadvantage, of course, is that the vehicle must be able to operate independently for extended periods of time. Data is often collected and stored on the vehicle, and there may be a significant time delay before it is

available for processing and action by the human in the loop. In some cases, fiber optic or acoustic communication links may be used to provide some data back to the host platform during the mission. With the current state of the art, AUVs are currently being applied to the detection and classification stages of the MCM mission. While currently only one in-service AUV system is dedicated to MCM, others are forthcoming, and summarized in Table 2.

Dedicated MCM AUVs

The Nearterm Mine Reconnaissance System (NMRS), built by Northrop Grumman, is a submarine-launched semi-autonomous system for mine field mapping. The system is carried onboard a submarine with the vehicles, operator consoles, tether, winches and other system components housed like torpedoes on the standard storage racks. The vehicle is launched and recovered through the torpedo tube using a drogue that provides a docking point to haul the vehicle back in. The vehicle is battery operated, using silver-oxide batteries and communicates with the mother submarine via a fiber optic cable. The system will have the ability to return to the submarine for autonomous recovery should the communication link be broken. The vehicle is 0.53 m in diameter and 5.2 m long. Onboard the 1,020-kg vehicle is a sensor suite made up of a forward-looking sonar for detection and classification of mine-like objects in the water column and a side-looking sonar to handle the bottom targets. The initial operational capability (IOC) of the NMRS was 1999.

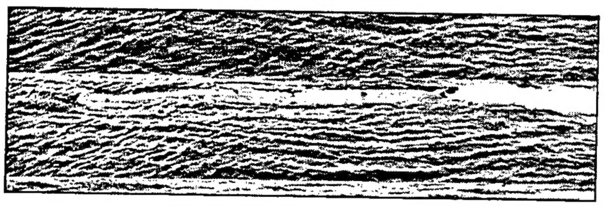

Figure 3: The Nearterm Mine Reconnaissance System

A contract was awarded to Boeing in 1999 for production of the Long term Mine Reconaissance System (LMRS) to replace the interim NMRS. Unlike the NMRS, the LMRS will be fully autonomous with a planned IOC of 2003. The vehicle concept will remain similar to the NMRS, with a full sensor suite to locate and classify mine-like objects, but the requirements will be more stringent. The goal of the system is to achieve a sortie reach of 120 nm with a total system area coverage of 650 square nm.

Developmental and Prototype Systems

As with the ROVs, there are many AUVs available internationally. A recent survey counted over 60 vehicles openly operating world-wide [Oceans 1999]. Many of the functions served are similar to MCM tasks: performing a bathymetry survey requires much the same capabilities as searching an area for mine-line contacts. A representative sampling for AUVs is described below, emphasizing the systems being considered for MCM operations.

Cetus is a small, hydro-dynamic AUV, designed by Lockheed Martin for mine countermeasures. For an AUV to be useful in performing tasks such as inspection, identification, recovery, mine disposal, etc., it must be able to hover and hold position in the water column. Cetus is 1.8 m long, 0.8 m wide and 0.5 m high and weighs about 150 kg in air with full payload. The AUV is rated to 198 m with aluminum pressure vessels and 3,962 m with titanium pressure vessels. The vehicle is configured with two main thrusters aft and three vertical thrusters for hovering. Cetus is currently powered by lead acid batteries and has a maximum speed of 5 knots and range of 40 km. The hull is fabricated from rotary molded high impact plastic.

In 1988, DARPA contracted to Charles Stark Draper Laboratory, Inc. to design and build advanced AUVs that could be used to demonstrate specific military missions such as Mine Reconnaissance and Search. Two vehicles were built, each just over 10.7 m long and 1.1 m in diameter. Utilizing silver-zinc batteries, the vehicles were capable of an endurance of 24 hours at 10 knots. Maximum depth capability was 457 m. One of the three missions was the Autonomous Minehunting and Mapping Technologies (AMMT) program. Lockheed Missiles and Space Corporation developed the Mine Search System payload which included a mission controller, fiber optic tether and tether management system. The goal was accurate reconnaissance and penetration of a suspected minefield and/or safe guidance of a submarine through a minefield while under semi-autonomous control. The MSS configured UUV successfully conducted the semi-autonomous minefield survey and transferred the data to the host via radio from a rendezvous point.

The REDERMOR is a vehicle designed by GESMA: Groupe d'Estudes Sous-Marines de l'Atlantique in Brest, FRANCE. It is an experimental AUV platform, developed during the French-British collaborative Remote Mine Hunting Project. The aim of the project is to compare several mine-hunting concepts in terms of efficiency and performance. The vehicle is very modular, and may be configured to operate in either a remotely-operated or autonomous mode. Sea trials have taken place in 1996, 1997, 1998, and 1999, demonstrating a variety of applicable technologies.

Hugin is one of the first commercially operational AUVs, developed by the Norwegian Defence Establishment and Kongsberg-Simrad. The program was originally funded by the military for minehunting, submarine offboard sensors, anti-submarine warfare, and reconnaissance. It is now being commercially employed for bathymetric surveys in support of the oil and gas industry.

Maridan of Denmark completed the Martin AUV in 1995 and began sea trials in 1996. This AUV was developed for oceanographic and commercial surveys to 600 m of water. The AUV utilizes a "flat fish" low drag hull design and is large enough to carry survey equipment such as pipeline tracking sensors. Martin is about 4.6 m long, 1.1 m wide and 0.6 m high, weighing about 1000 kg in air. Power is provided by 5 kWh lead acid batteries resulting in a duration of 25 hours and a maximum range of about 48 miles (77 km). Speed range is 2-5 knots. The vehicle uses a RESON SeaBat sonar for obstacle avoidance, an EDO Doppler Speed log, KVH gyro, Phillips autopilot and pressure gauge for navigation sensors and also carries a video camera. Communications between the vehicle and the surface ship are via a 50 kHz, 200 bps acoustic modem.

OTHER VEHICLE TYPES

While most of the active MCM vehicles are ROV's, some other types have also shown great promise, particularly in light of emerging operational needs. Surface-based systems, such as the ISE Dolphin, can be used to cover large areas, performing detection and classification in-stride with surface craft operations. The basic concept is to provide over-the-horizon mine reconnaissance using the semi-submerged, diesel powered, ROVs to tow sensors below the surface on a retractable tow cable. This technique underscores the new doctrine of placing the search sensors in front of the ships to locate the mines, instead of driving the ships over the mines while looking for or neutralizing them. The US Navy has investigated the use of such vehicles in programs such as the Remote Minehunting Operational Prototype (RMOP) and has now focused on the Remote Minehunting System (RMS), being produced by Lockheed Martin-Perry Technologies with an IOC of 2005.

For very shallow water and surf zone operation, a variety of crawling vehicles are being considered which may either function robotically or autonomously. The Office of Naval Research (ONR) and the Defense Advanced Research Projects Association (DARPA) have sponsored a significant amount of development of crawling robots based on crabs and other surf zone life. One of the most notable of these is Ariel, developed by IS Robotics. With six crab-like legs, Ariel can scramble over rocks and obstacles while maintaining solid contact with the bottom. The vehicle can operate equally effectively right side up or upside down, allowing great versatility and recovery capability in the tough surf environment.

TECHNOLOGY CONSIDERATIONS

All the undersea vehicle technologies contribute to the effective utilization of MCM vehicles, particularly those of communications, energy, sensors, navigation and control.

Energy has long been a major consideration for the performance of extended vehicle missions. When one moves away from surface supplied power, the energy source becomes a major factor in the design and efficiency of a vehicle system. Tradeoffs must be performed in light of energy density, cost, availability, and safety. The most commonly used energy source at this time is lead acid (Pb-Acid) batteries, favored due to their low cost, high reliability, and ready availability. Silver Zinc (Ag-Zn) batteries are used on some more developmental, high performance systems.

Communication is required between the vehicle and surface platform for both the transmission of commands to the vehicle and of data from the vehicle to the support platform. Primary issues to be considered when evaluating a mode of

Table 2: Autonomous MCM Vehicle Examples

Name	Manufacturer	Size (m)	Weight (kg)	Speed (kt)	Depth (m)	Range (km)
CETUS	Perry Technologies / Lockheed Martin USA	1.8 x 0.9 x 0.5	100-150	2.5 / 5	200 / 4000	20-40
DARPA UUV	Draper Laboratory USA	11 x 1.12 dia	6800	10	457	444
Hugin	Kongsberg Simrad Norway	4.8 long	700	4	600	300
Martin 200	Maridan Denmark	4.5 x 1.1 x 0.6	1400	4.9	100 (2000)	unknown
NMRS	Northrop Grumman USA	5.2 x 0.53 dia	1020	unknown	60	50
REDERMOR	GESMA France	6.0 x 1.0 dia	2500-2900	10	200	0.4

communication for an MCM task include available bandwidth, range between source and receiver, covertness, and the infrastructure required. Four main methods of communication between the vehicle and surface platform are routinely employed: hard wire tether (which may or may not contain an optical fiber), both expendable and reusable optical fiber, acoustic, and R/F. As autonomous systems become more common, non-tethered communications will be increasingly important.

Navigation is a key issue in MCM applications from the initial detection and mapping of mine-like contacts to the reacquisition of a target for identification and neutralization purposes. Depending on the desired goal, the accuracy of a vehicle navigation system must either allow the avoidance of mine targets for a safe transit of a ship or be sufficiently precise to allow the reacquisition of the target with on-board sensors.

The degree of autonomy and control available is one of the thorniest problems in vehicle design today. In the MCM world, there is a marked trend towards automated systems, particularly those performing the detection and classification functions. Those systems performing identification and neutralization are still generally teleoperated ROVs.

Sonars are the principal sensors in the MCM arena, used for detection, classification, and target relocation. Forward looking sonars are most commonly used for the initial detection functions, with side scan used for classification. A wide variety are currently in use, with continuing improvements in range, resolution, and associated data processing.

Visual images are considered key for the identification of an object as a mine. In a typical mine-field situation, particularly in the littoral zone, there will be many non-mine objects that appear mine-like to MCM sonars. Each of these must be positively identified as a mine or non-mine, which generally requires visual confirmation. Other sensors are being investigated for the detection and identification of mines, including both magnetic and chemical sensing techniques.

Payloads for MCM vehicles generally consist of either neutralization charges for the elimination of bottom mines or cable cutters for the moored mines. Auxiliary technologies are also playing important roles- the increase in computer graphic and visualization capabilities has contributed greatly to sensor integration, simulation, and training issues.

CONCLUSIONS

With the emphasis on littoral warfare and low intensity conflicts, MCM capabilities are becoming increasingly important in today's battle plan. Remotely operated vehicles currently play a key role world-wide in the identification and neutralization of undersea mines. Autonomous vehicles are now emerging as effective platforms for the detection and classification functions as well. New mission requirements such as wide area coverage and littoral operations will lead to further developments in vehicle types and capabilities.

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